AN EXPERIMENTAL INVESTIGATION OF MICROSTRIP PROPERTIES ON SOFT SUBSTRATES FROM 2 TO 40 GHz

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ABSTRACT

Dispersion and loss characteristics of microstrip lines on 10 mil and 31 mil electrodeposited and electroless copper clad-Teflon substrates were experimentally obtained from 2-40 GHz. The roles of surface roughness and radiation in total loss are examined.

INTRODUCTION

Extensive theoretical calculations and formulations on microstrip loss and dispersion are available in the literature, but there exists a dearth of experimental information, especially on low dielectric, Teflon-type substrates above X-band. These soft laminates are used extensively when thermal and mechanical stresses impose a problem, overcoming the difficulties associated with ceramic-type materials. Teflon substrates are being used in microstrip to waveguide transitions for the packaging and testing of Monolithic Microwave Integrated Circuits (MMIC) (1). In addition, soft substrates are used in high speed digital interconnections and microstrip patch antennas. Benefits are also realized from a reliability perspective, making these laminates viable candidates whenever larger circuit dimensions are tolerable. Their practicality becomes apparent in the millimeter-wavelengths where it is often desirable to have larger dimensions (2).

An experimental investigation was initiated to accurately characterize microstrip properties on these soft substrates. Specifically, an analysis of total microstrip loss and dispersion (variation of phase velocity with frequency) was performed on 10 and 31 mil substrates from 2 to 40 GHz using 50 ohm lines. A novel technique was used for the high frequency measurements. Incorporated in the total loss is the effect of surface roughness, which was clearly evidenced when the results were compared with loss theories for ideally smooth surfaces. In addition, the contribution of radiation to total loss was investigated and its severity below 20 GHz is reported. Fringing effects are also included in the results.

EXPERIMENTAL PROCEDURE

Linear open circuit $n\lambda/2$ microstrip resonators were fabricated by conventional printed circuit techniques on copper-clad Teflon and Teflon/glass substrates. The technique utilized two 50 Ω microstrip lines on a single substrate; a short line of length L_1 with a fundamental $\lambda/2$ resonance at F_1, and a long line of length $L_2 \approx 2L_1$ with a second harmonic λ resonance at $F_2 \approx F_1$. By using two lines, the end (fringing) effects are subtracted from the final results. For frequencies below 20 GHz, a conventional coaxial-to-microstrip transition was used to feed the RF signal to the resonator via a symmetrical 4 or 6 mil gap. The wider gap was used for the thicker substrates since coupling is proportional to substrate height. It is undesirable to deduce data from an overcoupled resonator since the resulting frequency response curve is quite broad which inhibits an accurate analysis. The loading which results from the overcoupling also tends to shift the resonant frequencies and distort the effect of dispersion. Measurements from 18 to 40 GHz were performed using a novel waveguide-to-microstrip transition in line with the resonator via a similar gap (Fig. 1). Both techniques utilized HP network analyzers to provide the swept measurements. Losses were evaluated in terms of the quality factor (Q). The unloaded quality factor (Q_0) must be derived from the raw data which yields the loaded Q. For an undercoupled resonator, it can be shown that:

$$Q_0 = \left\{1 + \frac{1 - 10^{-\Gamma/20}}{1 + 10^{-\Gamma/20}}\right\} \frac{F_0}{\Delta F} \qquad (1)$$

where Γ is the magnitude of the reflection coefficient at the resonant frequency F_0 and ΔF is the 3 dB bandwidth (3,4). The effective permittivity ($\varepsilon_{eff}(F)$) can be evaluated from the resonant frequencies of the two lines (F_1 and F_2) and their physical lengths (L_1 and L_2). Line lengths were resolved to within 3 μm using a commercial optical comparator. The measured effective permittivity is:

$$\varepsilon_{eff}(F) = \left\{\frac{nc(2F_1 - F_2)}{2F_1F_2(L_2 - L_1)}\right\}^2 \qquad (2)$$

where c is the speed of light and n is the order of resonance (5).

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RESULTS AND DISCUSSION

Microstrip Dispersion

The effect of dispersion is presented in Figs. 2 and 3. There is fair agreement with theory (6,7) although some doubt is cast on the precise value of the static (zero frequency) effective permittivity. Several theories offering closed form expressions were evaluated, with the formulation developed by Bahl and Garg (8) providing the closest approximation to the value projected by the experimental results. Figure 2 provides data for a pure Teflon (low dielectric constant) substrate. The dispersive behavior of both 10 and 31 mil substrates is considered as well as the effect of shielding. In general, the data derived from shielded resonators falls below theoretical and unshielded experimental values. Figure 3 represents dispersion effects of a glass microfiber reinforced PTFE composite material with a similar dielectric constant. The plot of Getsinger's model used the empirically optimized parameter G as developed for sapphire (9), and the equivalent isotropic relative permittivity ε_{req} was equated to ε_r.

Microstrip Losses

Results on net microstrip loss and radiation for 10 mil substrates are presented in Figs. 4 and 5. The figures depict the contribution of conductor, dielectric, and radiation losses on total Q, which is inversely proportional to loss (10,11). The dielectric loss curve does not fall within the graphs due to the low loss tangents for the materials, which were 0.0009 for the material in Fig. 4 and 0.00045 for Fig. 5 at 10 GHz. It is conceded that the loss tangent increases somewhat with frequency, however, an accurate description of its behavior was unavailable. Hence, the reported values at 10 GHz were used and assumed constant throughout the band. The effect on the theoretical curves is believed minimal.

Figure 4 provides experimental data for several substrates with similar characteristics except for surface morphology. The measured root mean square (rms) interfacial roughness for these substrates was between 0.44 and 0.77 μm. Of noteworthy significance is the magnitude of the difference between the theoretical (smooth interface) Q and the experimental Q values. The disparity, which results from the interfacial roughness between the copper cladding and substrate, is not evident in Fig. 5. The data presented in Fig. 5 are for a relatively smooth interface, where the rms roughness was 0.27 μm. There is good agreement with the theoretical calculation. The points which rise above theoretical values at the high frequencies are attributed to normal scatter from measurement errors at these frequencies. The effect of the metal-polymer interface on relative attenuation has been discussed elsewhere (12).

In addition to interfacial roughness, the role of radiation in total microstrip loss is demonstrated. The experimental data show a dramatic decrease in the radiation Q (increase in radiation loss) between 10 and 15 GHz for the 10 mil substrates. Theory (13) predicts this effect at a much lower frequency, although the disparity was much less pronounced for the thick (31 mil) substrates. Radiation loss varies as the square of the substrate thickness, becoming the dominant loss mechanism above $\approx$3 GHz for microstrip on thick, low dielectric constant materials, as evidenced by experiments. A further effect of radiation is fringing effects which tend to electrically extend the length of a microstrip line (resonator) beyond its abrupt physical end. Figure 6 shows the combined electrical extension occurring at the open end and the coupling gap. As one would expect from the previous results, the fringing is considerably more extensive on the thick substrate. An interesting effect, however, is noted for the thin substrate i.e., there is a significant increase in magnitude of the fringing between 5 and 10 GHz. This observation correlates with the sudden decrease in the radiation Q (Q_R) occurring near 10 GHz. A similar effect presumably occurs for the thick substrates, probably near 1 or 2 GHz, although no resonators were evaluated at these frequencies to verify this assumption.

CONCLUSIONS

Dispersion has been evaluated for 10 mil and 31 mil Teflon-type substrates. The results correlated fairly well with various theories although the static effective permittivity seems to be somewhat overestimated. Also, it is evident that dispersive effects are quite pronounced even on thick, low dielectric constant substrates and it is recommended that it not be neglected in any frequency range as has been suggested in the past. Data for the shielded resonators fell slightly below that for the unshielded case as predicted by theory.

Total microstrip loss was evaluated and compared to theory up to 40 GHz. The effect of surface roughness on total microstrip loss was demonstrated. It was shown that a significant increase in loss results when the surface roughness is on the order of 0.5 μm even at lower frequencies. Conversely, an rms roughness of 0.25 μm seems to be negligible in terms of increased loss.

The theoretical curve for radiation loss developed by Belohoubek and Denlinger (13) portrays radiation dominating losses above $\approx$8 GHz, whereas the experiments convey a somewhat higher frequency. The results indicate that Q_R is dominant above $\approx$15 GHz and suggest that shielding should be a fundamental requirement above $\approx$10 GHz when using 50 ohm (or wider) lines and the given laminates. In addition, the reported fringing effects provide insight into the radiation phenomenon and information which may be useful when designing microstrip circuitry.

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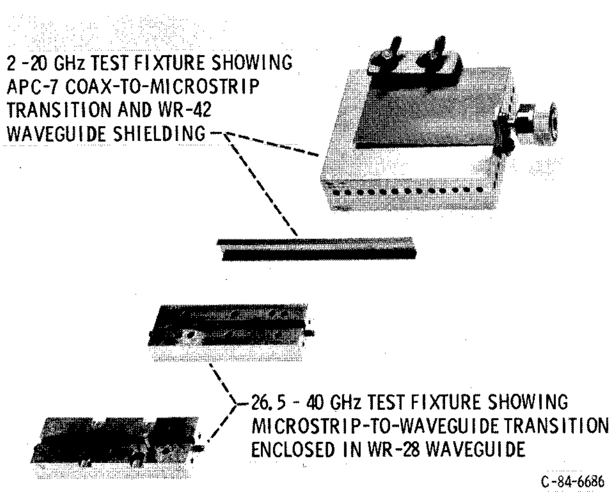

Figure 1. - Resonator test fixtures and shielding hardware. The fixture at top features a λ and λ/2 resonator on a 31 mil substrate. The bottom fixture depicts a transition to waveguide in series with the resonator.

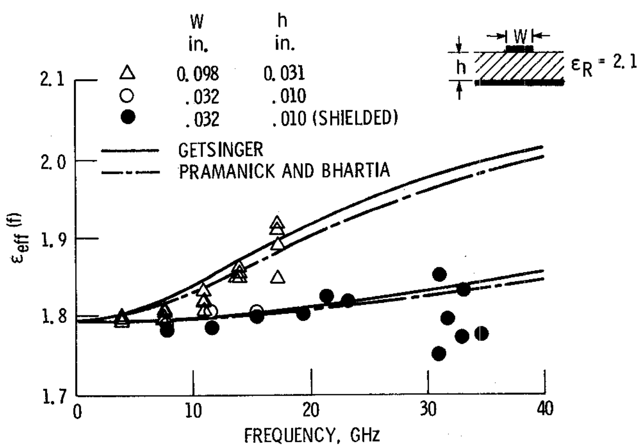

Figure 2. - Effective microstrip permittivity versus frequency for a 50 ohm line on the commercially available substrate Cu Flon, manufactured by Polyflon Corporation.

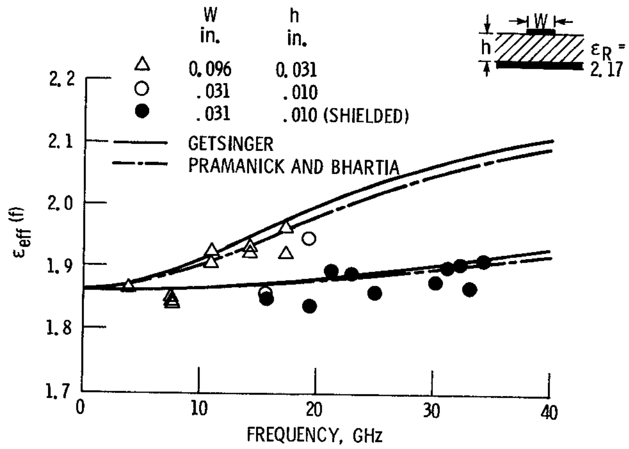

Figure 3. - Effective microstrip permittivity versus frequency for a 50 ohm line on the commercially available substrate Duroid 5880, manufactured by Rogers Corporation.

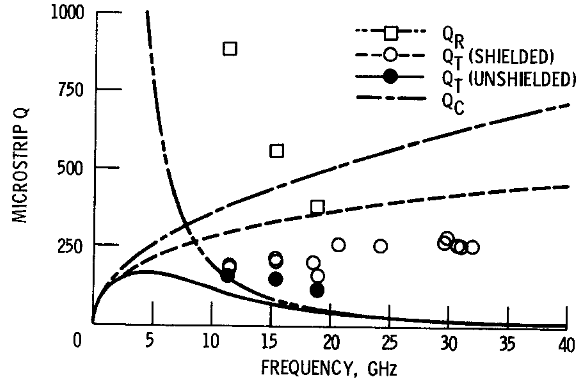

Figure 4. - Cumulative effects of various contributions to microstrip loss on a 10 mil electrodeoposited copper clad-Teflon/glass substrate with a fairly rough interface. The data is for 50 ohm $\lambda/2$ resonators.

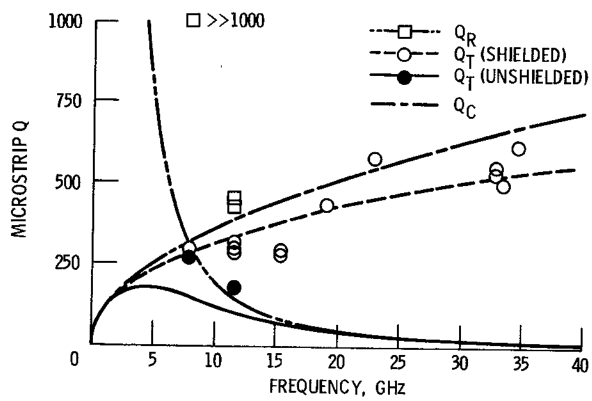

Figure 5. - Cumulative effects of various contributions to microstrip loss on a 10 mil electroless copper clad-Teflon substrate with a fairly smooth interface. The data is for 50 ohm $\lambda/2$ resonators.

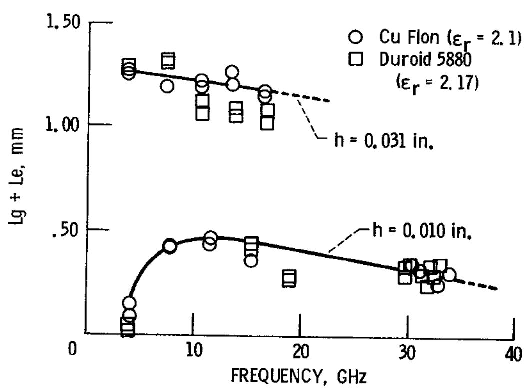

Figure 6. - Apparent electrical extension of 50 ohm $\lambda/2$ microstrip resonators. Lg + Le represents the sum of the extension at the gap and open end.